String Phenomenology:
Type II/F-Theory Perspective

Focus on particle physics & D-branes:

I. Type II (w/ D-branes at small string coupling)

→ Standard Model & GUT's

Recent developments: Non-perturbative effects (D-instantons)

→ new hierarchy for couplings

II. F-theory (string theory w/ D-branes at finite coupling)

→ primarily (local) SU(5) GUT's

→ instantons

time permitting

III. Conclusions/outlook

I. Particle Physics implications (Type II):

Recent focus: landscape of realistic D-brane quivers w/ D-instantons

MSSM's w/ realistic fermion textures

M.C., J. Halverson, R. Richter, & P. Langacker '09-'10

General MSSM quivers & Additional Matter

(to make it compatible w/ global constraints) → stringy inputs on exotic matter

M.C., J. Halverson,P. Langaceker,1108... appears tonight on hep-ph

→ c.f., also J. Halverson's talk in the morning parallel session

II. D-instantons: recent focus on Type IIB & F-theory

F-theory aspects (multi-prong approach): zero modes& superpotential

M.C., I. Garcia-Etxebarria, J. Halverson 1107.2388

(also, 1003. 5337, 1008.5386 &M.C., I. Garcia-Etxebarria, R. Richter 0911.0012)

Perturbative String Theories → (finite) theory of quantum gravity

Green&Schwarz'84

Phenomenologically promising

Recent (MSSM): Bouchard,M.C., Donagi'05 …

Anderson,Gray,Lukas`09… L. Anderson's talk in parallel session

Lebedev,Nilles,Raby,Ramos,Ratz Vaudrevange,Wingerter'07-'09

Heterotic E_8xE_8 string

Type IIA superstring

(closed)

Type IIB superstring

(closed)

Heterotic SO(32) string

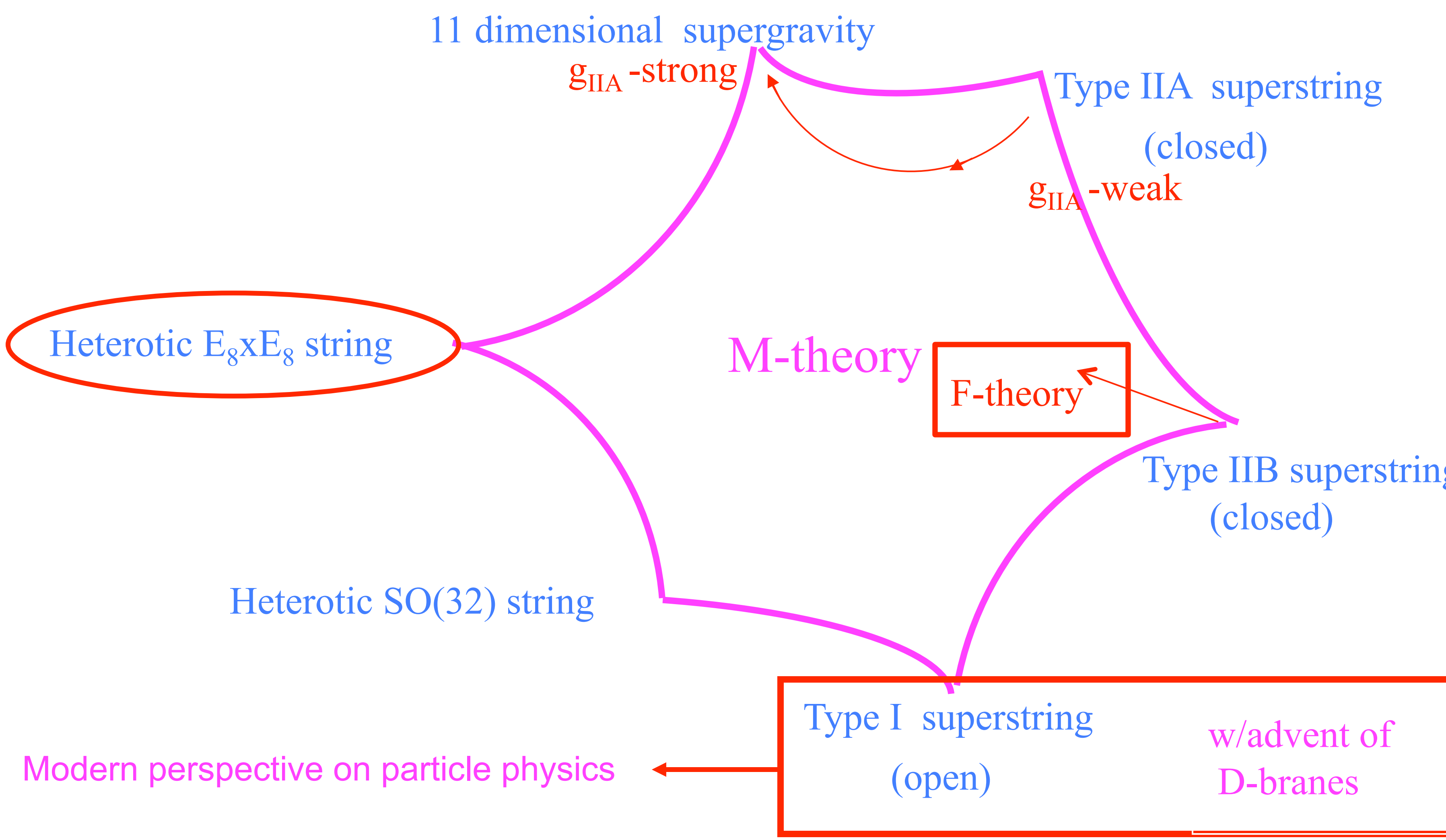
Type I superstring

(open)

Perturbative String Theories → (finite) theory of quantum gravity

Hull&Townsend'94
Witten'95

Non-perturbative Unification



Different String Theories related to each other by Weak-Strong Coupling DUALITY

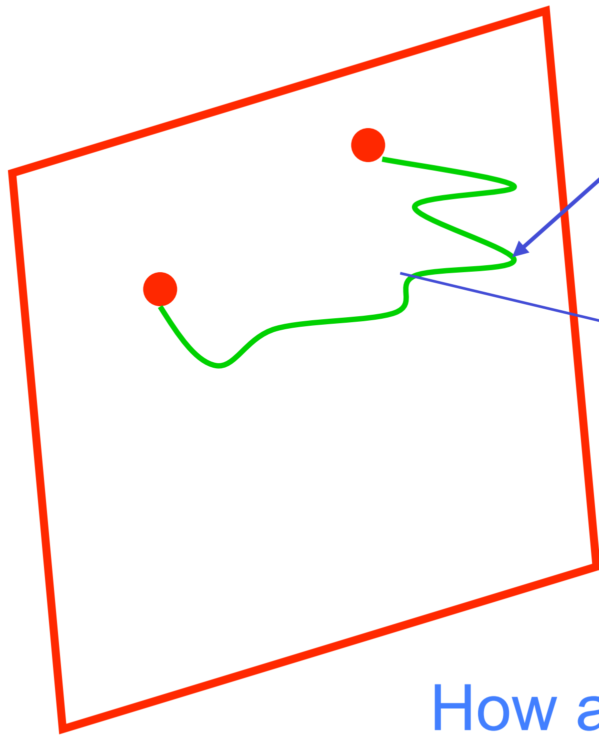
D-branes & Particle Physics →

Beautiful relation to particles & forces of nature - geometric

Open strings w/ charges at the ends

Ends ``attached " to boundary Dp – branes Polchinski'95

Extends in p+1 dim. world-volume



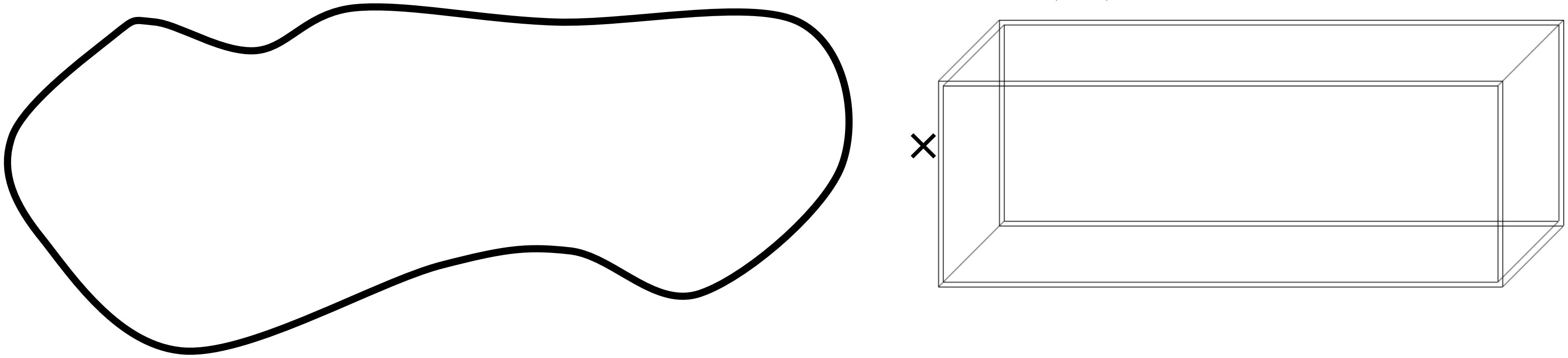
Quantum theory-string excitations
result in MASSLESS spin -1
Gauge bosons →
Photon, gluon, W,Z-bosons
live on the D-branes!

How about matter → compactification

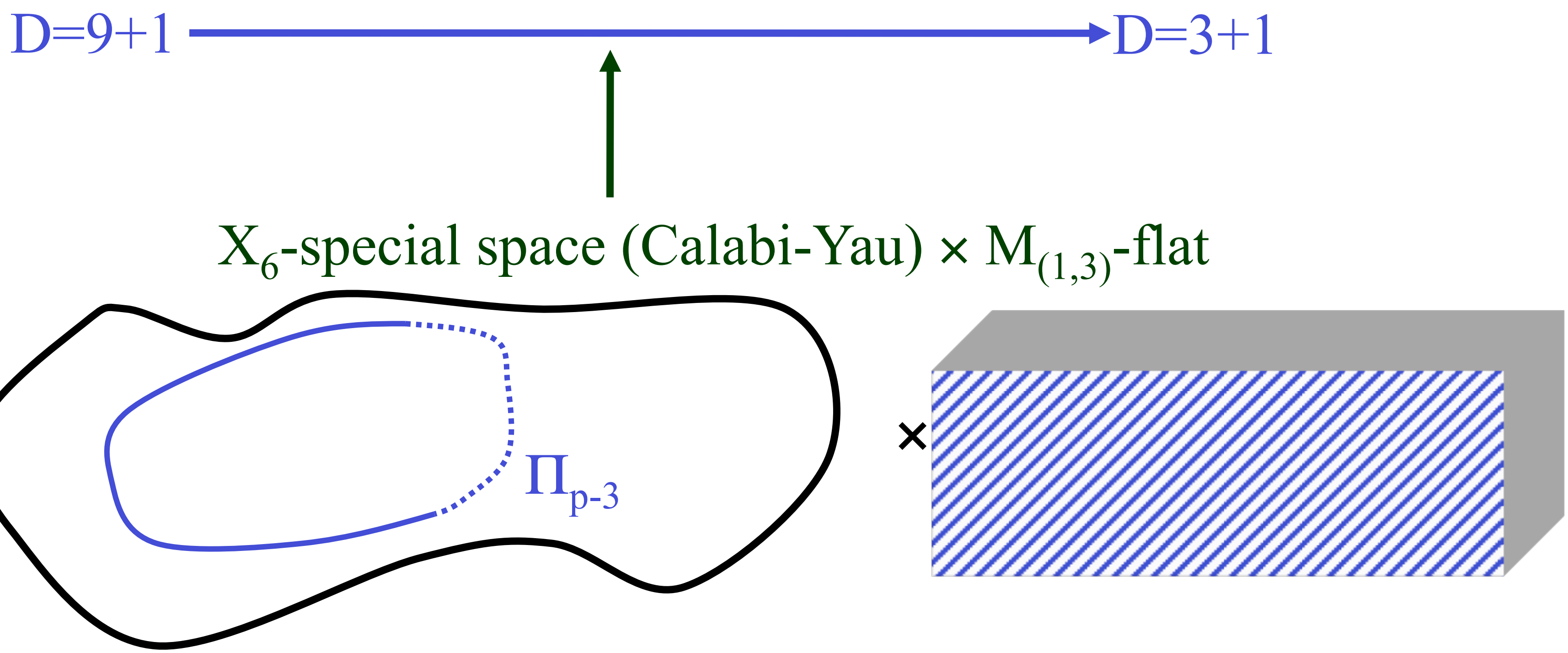
Compactification

D=9+1 $\longrightarrow$ D=3+1

X_6-special space (Calabi-Yau) × $M_{(1,3)}$-flat



Compactification

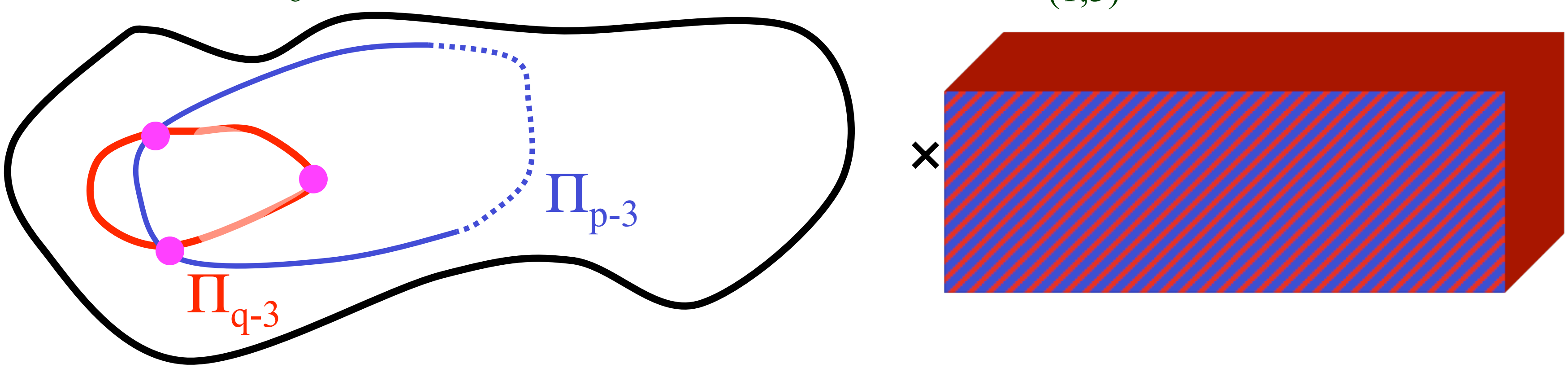


D p-branes – extend in p+1 dimensions:
3+1-our world $M_{(3,1)}$;(p-3)-wrap Π_{p-3} cycles of X_6

Compactification

$D=9+1 \longrightarrow D=3+1$

X_6-special space (Calabi-Yau) × $M_{(1,3)}$-flat



D p-branes – extend in p+1 dimensions:
3+1-our world $M_{(3,1)}$;(p-3)-wrap Π_{p-3} cycles of X_6

D q-branes – extend in q+1 dimensions:
3+1-our world $M_{(3,1)}$;(q-3)-wrap Π_{q-3} cycles of X_6

$\Pi_{q-3} \cap \Pi_{p-3}$
$\Pi_{q-3} \subset \Pi_{p-3}$

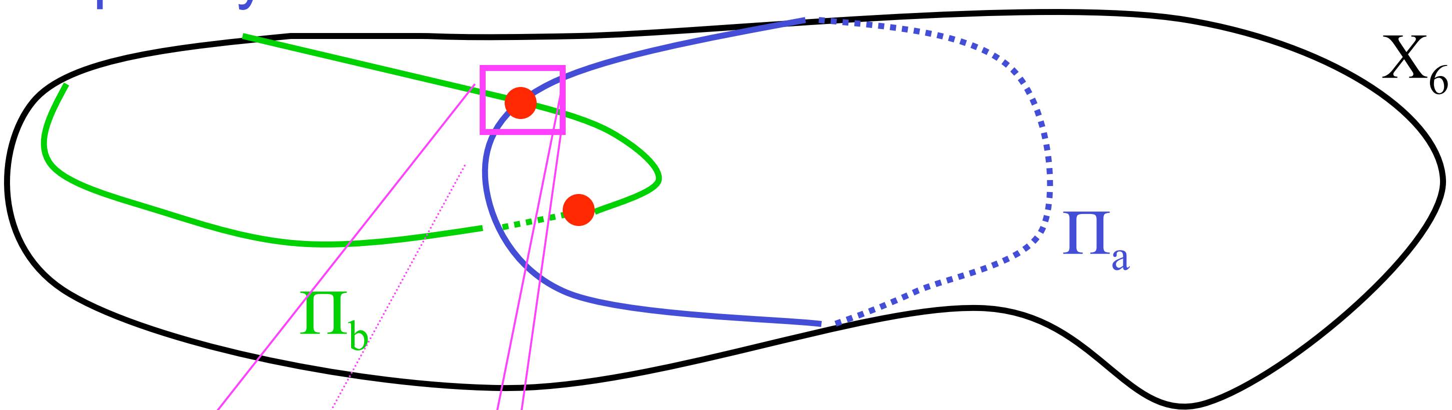
$\Downarrow$

Rich structure

D-branes at singularities & Wilson lines: **Aldazabal et al. 98....**
M.C.,Wang&Plümacher'00;M.C.Wang&Uranga'01…

Intersecting D6-branes

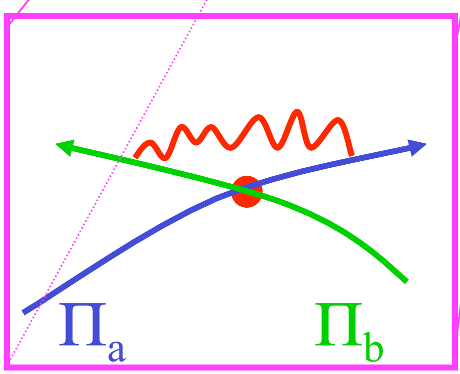
wrap 3-cycles Π



In internal space intersect at points:

Number of intersections $[\Pi_a] \circ [\Pi_b]$ - topological number

Geometric origin of family replications!



Berkooz, Douglas & Leigh '96

At each intersection-massless string excitation-

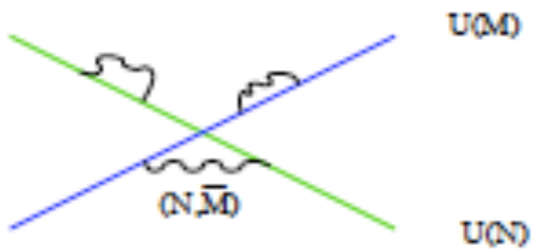
spin ½ field ψ - matter candidate

Geometric origin of matter!

Type II w/ D-branes →
fertile ground for particle physics model building
[Pedagogical review: TASI'10 lectures, M.C., Halverson arXiv:1101.2907]

Type IIA w/intersecting D-branes → key features of SM & SU(5) GUT
spectrum: non-Abelian gauge symmetry, chirality & family replication

Geometric



Representation	Multiplicity
$(\overline{a}, b)$	$\pi_a \circ \pi_b$
$(\overline{a}, \overline{b})$	$\pi_a \circ \pi'_b$
$\substack{\square \\ \square}_a$	$\frac{1}{2}(\pi'_a \circ \pi_a + \pi_{O6} \circ \pi_a)$
$\square\square_a$	$\frac{1}{2}(\pi'_a \circ \pi_a - \pi_{O6} \circ \pi_a)$

Large classes (order of 100's) of supersymmetric,
globally consistent (Gauss's law for D-brane charge)
SM-like & GUT constructions; also coupling calculations

[M.C. ,Shiu, Uranga'01]...

[M.C. Papadimitriou '03],
[Cremades, Ibáñez, Marchesano'03]...

Recent developments:

New types of D-instantons: introduced to generate certain perturbatively absent couplings for charged sector matter

[Blumenhagen,M.C.,Weigand, hep-th/0609191]
[Ibañez,Uranga, hep-th/0609213]
- charged matter coupling corrections

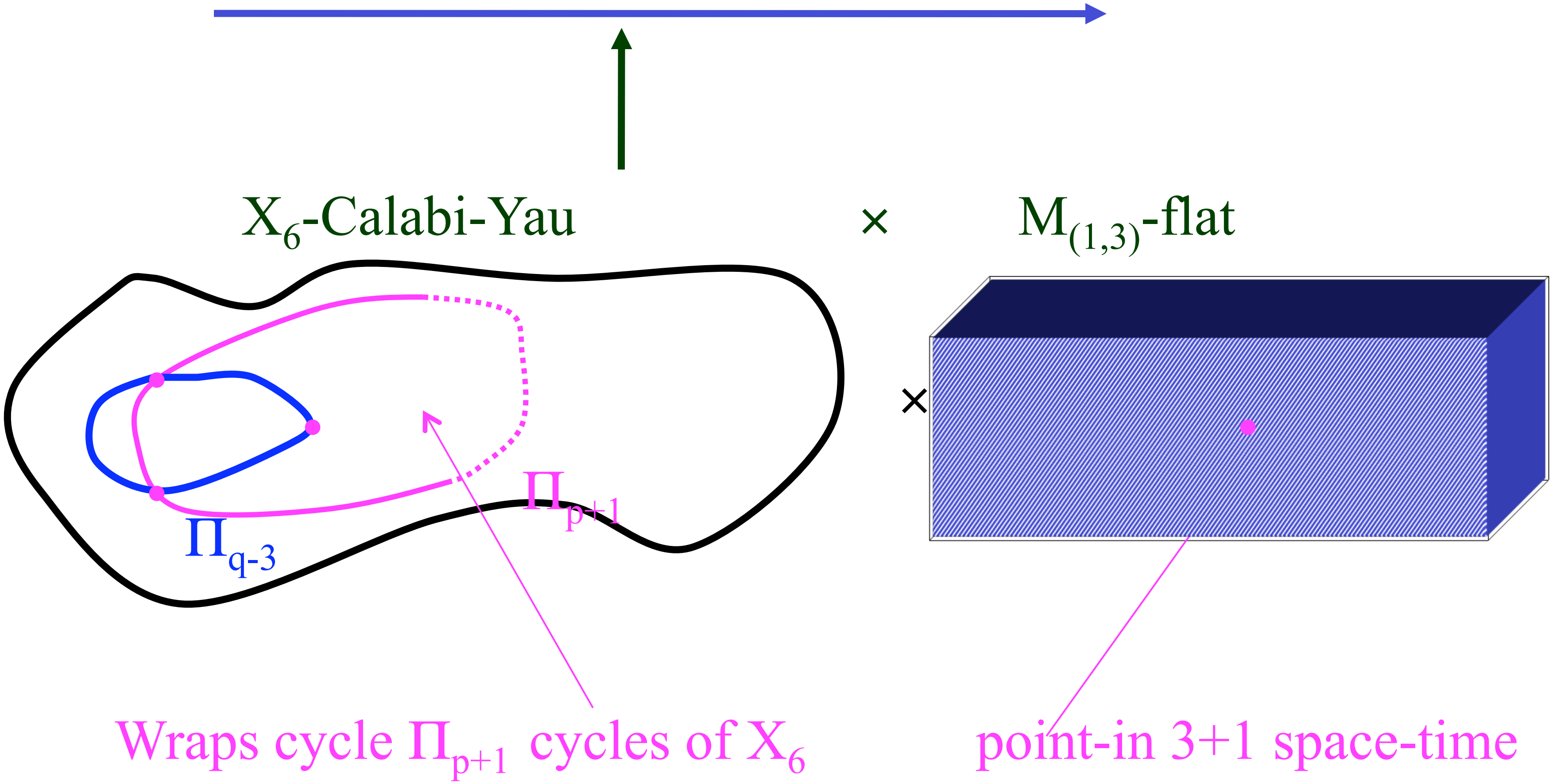
. . .

[Florea,Kachru,McGreevy,Saulina, 0610003]
- supersymmetry breaking

Review: [Blumenhagen, M.C., Kachru, Weigand, 0902.3251]

Encoded in non-perturbative violation of ``anomalous'' U(1)'s

D-Instanton - Euclidean D-brane backgound



New geometric hierarchies for couplings:

$$\mathcal{R}e\left(e^{-S_{E2}}\right) = e^{-\frac{2\pi}{\ell_s^3 g_s}\mathrm{Vol}_{E2}} = e^{-\frac{2\pi}{\alpha_{\mathrm{GUT}}}\frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{D6}}}$$ stringy!

Instanton can intersect with physical Dq-brane

→ charged zero modes generate non-perturbative couplings

Rigid O(1) instantons → direct contribution to superpotential

I. Wrap rigid cycles homologically the same as orientifold cycles-

Neutral zero modes $\overline{\tau}^{\dot{\alpha}}$ projected out [Argurio et al.0704.0262]

$\longrightarrow$ 4 bosonic modes x_E^μ & only 2 fermionic modes θ_α

yield directly superpotential measure: $\int d^4x_E\, d^2\theta$

$$W \sim e^{-S^{cl}_{E2}} \prod_i \Phi_i,$$

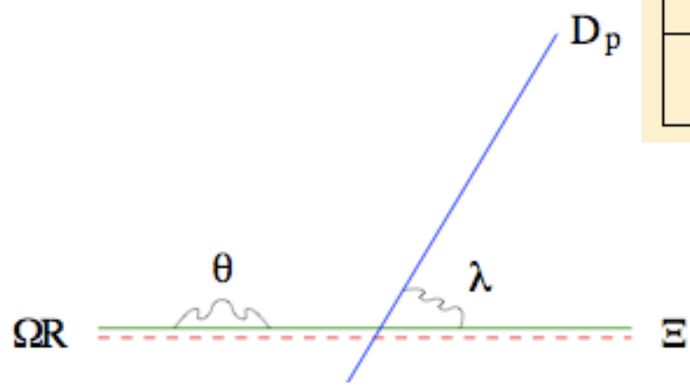
II. Charged Zero modes from strings between $E2$ and $D6_a$:

$\longrightarrow$ Localized at each intersection of $E2$ and $D6_a$:

One fermionic zero mode λ_a per intersection

Stringy & Geometric!

Zero modes	Reps	Number
$\lambda_{a,I}$	$(-1_E, \square_a)$	$I = 1, \dots, [\Xi \cap \Pi_a]^+$
$\overline{\lambda}_{a,I}$	$(1_E, \overline{\square}_a)$	$I = 1, \dots, [\Xi \cap \Pi_a]^-$
$\lambda_{a',I}$	$(-1_E, \overline{\square}_a)$	$I = 1, \dots, [\Xi \cap \Pi'_a]^+$
$\overline{\lambda}_{a',I}$	$(1_E, \square_a)$	$I = 1, \dots, [\Xi \cap \Pi'_a]^-$



III. Develop conformal field theory instanton calculus

[Blumenhagen, M. C., Weigand, hep-th/0609191, ...]

Building blocks: disc-level couplings of two λ modes to matter Φ_{ab}: $S = \int_\Xi \lambda_a\, \Phi_{ab} \overline{\lambda}_b$

Specific Examples:

i Majorana neutrino masses original papers,...

ii Nonpert. Dirac neutrino masses [M.C.,Langacker, 0803.2876]

iii 10 10 5 GUT couplings

[Blumenhagen,M.C.,Lüst,Richter,Weigand,0707.1871]

one-instanton effect $\longrightarrow g_s \to 1$ (M-theory on G_2)

iv Polonyi-type couplings $\longrightarrow$

[Aharony,Kachru,Silverstein 0708.0493] [MC,Weigand 0711.0209,0807.3953]
[Heckman,Marsano,Saulina,Schafer-Nameki,Vafa 0808.1286] ...

Examples of such instanton induced hierarchical couplings primarily for local Type IIA toroidal orbifolds SU(5) GUT's

Challenge: global models→Type I/IIB/F-theory (algebr. geom.)

i. Type I GUT's on compact elliptically fibered Calabi-Yau
First global chiral (four-family) SU(5) GUT's w/ D-instanton generated Polonyi & Majorana neutrino masses

[M.C.,T.Weigand, 0711.0209,0807.3953]

ii. Global Type IIB GUT's : 1010 5_H non-perturbative coupling
(two family) SU(5) GUT on CY as hypersurface in toric variety

[Blumenhagen,Grimm,Jurke,Weigand, 0811.2938]

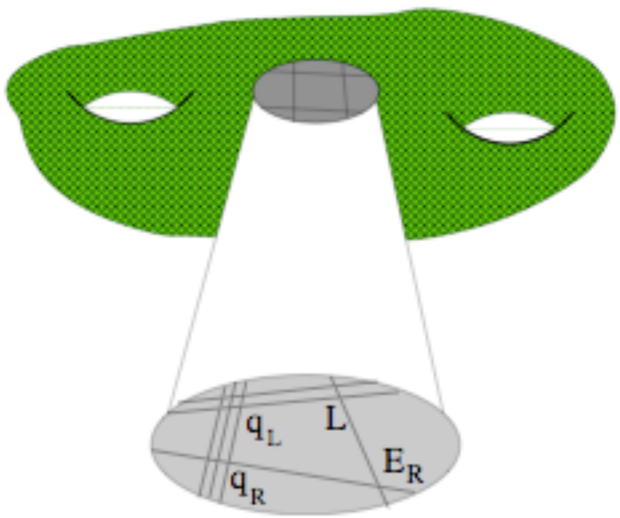
iii. Global F-theory lift [M.C., I. Garcia-Etxebarria, J. Halverson,003.5337]

[Develop a code to calculate zero modes/spectrum in Type IIB and F-theory on toric varieties; code w/ new efficient technique →
[Blumenhagen, Jurke, Rahn & Roschy, 1003.5217]]

Most examples w/ O (1) instantons addressed SU(5) GUT's
How about Standard Model?

Adressed for local Madrid quiver [Ibanez,Richter, 0811.1583]

Systematic Analysis of D-Instanton effects for MSSM's quivers
(compatible with global constraints)



Landscape analysis of MSSM w/ realistic fermion textures
[M.C., J. Halverson, R. Richter, 0905.3379; 0909.4292; 0910.2239]

Stringy Weinberg operator neutrino masses (examples of low string scale)
[M.C., J. Halverson, P. Langacker, R. Richter, 1001.3148]

Singlet-extended MSSM landscape
[M.C. J. Halverson, P. Langacker, 1006.3341]

→ c.f. J. Halverson's talk in the parallel session

Bottom-up approach initiated [Aldazabal,Ibanez,Quevedo,Uranga'00]..
Related recent works: Specific 3-stack [Leontaris, 0903.3691]
Madrid quiver [Anastasopoulos, Kiritsis, Lionetto, 0905.3044]
SU(5) GUT's [Kiritsis, Lennek, Schellekens, 0909.0271]...
MSSM at toric singularities: [Krippendorf, Dolan,Maharana,Quevedo,1002.1790, 1106.6039]

Approach: Bottom-up quivers

Since spectrum and couplings geometric ⇒
efficient classification of key physics
[compatible w/ global constraints, but without delving into specifics of globally defined string compactifications]
[global conditions←→Gauss's law for D-brane charge←→stringy]

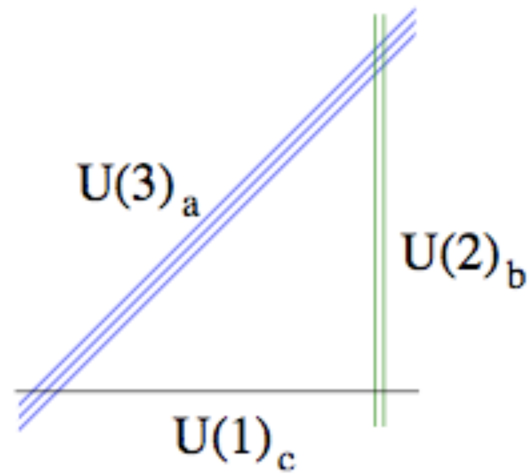
Quiver data: massless spectrum &
examination of couplings
[both perturbative & non-perturbative w/O(1)-inst.]

⇓

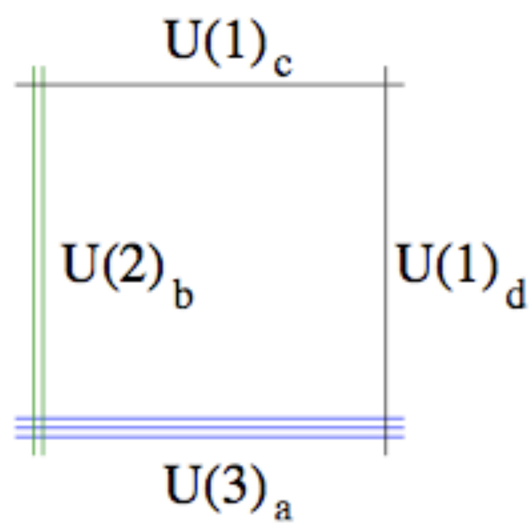
Probe ``quiver landscape''
to identify realistic quivers in the landscape of string vacua

Multi-stack MSSM quivers

Employ three-stack MSSM $U(3)_a \times U(2)_b \times U(1)_c$



& four-stack MSSM $U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d$



five-stack….

Four-stack set of MSSM models w/ 3 N_R & potentially viable fermion textures

[M.C., J. Halverson, R. Richter, 0905.3379]

Solution #	q_L		d_R			u_R		L			E_R			N_R				H_u				H_d
	(a,b)	$(a,\bar{b})$	$(\bar{a},c)$	$(\bar{a},\bar{d})$	$\lceil_a$	$(\bar{a},\bar{c})$	$(\bar{a},d)$	$(b,\bar{c})$	(b,d)	$(\bar{b},d)$	$(c,\bar{d})$	$\sqcup\sqcup_c$	$\sqcup\sqcup_d$	$\rceil_b$	$\sqcap_b$	(c,d)	$(\bar{c},\bar{d})$	(b,c)	$(\bar{b},c)$	$(b,\bar{d})$	$(\bar{b},\bar{d})$	$(\bar{b},\bar{c})$
1	3	0	3	0	0	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
2	3	0	2	0	1	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
3	3	0	1	0	2	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
4	3	0	0	0	3	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
5	3	0	0	0	3	0	3	0	0	3	0	0	3	3	0	0	0	1	0	0	0	1
6	3	0	3	0	0	2	1	0	0	3	0	2	1	2	0	1	0	0	0	0	1	1
7	3	0	3	0	0	3	0	0	0	3	2	1	0	2	0	0	1	0	1	0	0	1
8	3	0	3	0	0	3	0	0	0	3	0	2	1	2	0	0	1	0	1	0	0	1
9	3	0	3	0	0	3	0	0	0	3	1	2	0	2	0	1	0	0	1	0	0	1
10	2	1	3	0	0	1	2	0	0	3	0	0	3	0	0	0	3	1	0	0	0	1
11	2	1	3	0	0	1	2	0	0	3	3	0	0	0	0	3	0	1	0	0	0	1
12	2	1	3	0	0	3	0	0	0	3	3	0	0	0	0	0	3	1	0	0	0	1
13	2	1	3	0	0	3	0	0	1	2	3	0	0	0	0	0	3	0	1	0	0	1
14	1	2	3	0	0	3	0	0	3	0	3	0	0	0	0	0	3	1	0	0	0	1
15	0	3	0	3	0	0	3	3	0	0	0	1	2	0	3	0	0	0	0	1	0	1
16	0	3	0	0	3	0	3	0	3	0	0	0	3	0	3	0	0	1	0	0	0	1
17	0	3	0	0	3	0	3	1	2	0	1	0	2	0	3	0	0	0	0	1	0	1
18	0	3	0	0	3	0	3	3	0	0	2	0	1	0	3	0	0	0	0	1	0	1
19	0	3	0	0	3	0	3	3	0	0	0	1	2	0	3	0	0	0	0	1	0	1
20	0	3	0	0	3	1	2	1	2	0	2	0	1	0	3	0	0	1	0	0	0	1
21	0	3	0	0	3	1	2	1	2	0	0	1	2	0	3	0	0	1	0	0	0	1
22	0	3	0	0	3	1	2	3	0	0	3	0	0	0	3	0	0	1	0	0	0	1
23	0	3	0	0	3	1	2	3	0	0	1	1	1	0	3	0	0	1	0	0	0	1
24	0	3	0	0	3	2	1	0	3	0	3	0	0	0	3	0	0	1	0	0	0	1
25	0	3	0	0	3	2	1	0	3	0	1	1	1	0	3	0	0	1	0	0	0	1
26	0	3	0	0	3	2	1	2	1	0	2	1	0	0	3	0	0	1	0	0	0	1
27	0	3	0	0	3	2	1	2	1	0	0	2	1	0	3	0	0	1	0	0	0	1
28	0	3	0	3	0	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
29	0	3	0	2	1	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
30	0	3	0	1	2	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
31	0	3	0	0	3	3	0	1	2	0	1	2	0	0	3	0	0	1	0	0	0	1

Solutions for hypercharge $U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c - \frac{1}{2}U(1)_d$ - Madrid embedding

Concrete 5-stack model (benchmark)

(w/ three mass scales in top, bottom in charged lepton sector)

Sector	Matter Fields	Transformation	Multiplicity	Hypercharge
ab	q_L	$(a, \bar{b})$	1	$\frac{1}{6}$
ab'	q_L	(a, b)	2	$\frac{1}{6}$
ac'	u_R	$(\bar{a}, \bar{c})$	2	$-\frac{2}{3}$
ad'	u_R	$(\bar{a}, \bar{d})$	1	$-\frac{2}{3}$
aa'	d_R	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}_a$	3	$\frac{1}{3}$
bc'	H_u	(b, c)	1	$\frac{1}{2}$
bd'	L	$(\bar{b}, \bar{d})$	3	$-\frac{1}{2}$
be'	H_d	$(\bar{b}, \bar{e})$	1	$\frac{1}{2}$
ce'	E_R	(c, e)	2	1
ce	N_R	$(\bar{c}, e)$	1	0
dd'	E_R	$\Box\Box_d$	1	1
de	N_R	$(\bar{d}, e)$	2	0

Allows for full (inter- & intra-) family mass hierarchy via ``factorization of Yukawa matrices'' due to vector-pairs of zero fermion modes-stringy (technical, no time)

New: Stringy constraints & matter beyond the MSSM

[M.C., J. Halverson, P. Langacker,1108... tonight on hep-ph]

→ c.f., also J. Halverson's talk in the morning parallel session

I.Classify all possible MSSM quivers (three, four stacks)
study the additional matter needed to be compatible
with the global constraints - stringy inputs on exotic matter

3-stack analysis: global conditions ($T_{a,b,c}$=0) constraining, e.g., MSSM w/

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c \qquad T_a = 0 \qquad T_b = \pm 2n \qquad T_c = 0\, mod\, 3 \qquad \text{with } n \in \{0, \ldots, 7\},$$

w/ preferred additions: quasi-chiral Higgs pairs, MSSM singlets
hyperchargeless SU(2) triplets,&
various quark anti-quark pairs, all w/ integer el. ch.;
one (massless) Z' quiver

4-stack analysis: richer structure
sizable number of quivers w/ Z', including leptophobic (tuned);
additional structures: possible $SH_{\underline{u}}H_{d}$,; ν-masses;
exotics w/ fractional el. ch. …

II. Work in progress on axigluons w/ (stringy) quiver embedding

• 105 3-node quivers (≤ 5 additions)

Multiplicity	Matter Additions				
4	$\yng(2)_b,\ (1,3)_0$	$\yng(2)_b,\ (1,3)_0$	$\yng(1,1)_b,\ (1,1)_0$	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(\overline{a},\overline{b}),\ (\overline{3},2)_{-\frac{1}{6}}$
4	$\yng(2)_b,\ (1,3)_0$	$\yng(1,1)_b,\ (1,1)_0$			
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$\yng(1,1)_b,\ (1,1)_0$			
4	$\yng(2)_b,\ (1,3)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\yng(2)_b,\ (1,3)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(\overline{a},\overline{b}),\ (\overline{3},2)_{-\frac{1}{6}}$
4	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$			
4	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$		
4	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$\yng(1,1)_a,\ (\overline{3},1)_{\frac{1}{3}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(\overline{a},\overline{c}),\ (\overline{3},1)_{-\frac{2}{3}}$	$\yng(2)_c,\ (1,1)_1$
4	$\yng(2)_b,\ (1,3)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$		
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\yng(1,1)_b,\ (1,1)_0$				
4	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$\overline{\yng(2)}_b,\ (1,3)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$	
4	$\overline{\yng(2)}_b,\ (1,3)_0$	$\overline{\yng(2)}_b,\ (1,3)_0$	$\overline{\yng(1,1)}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	$\yng(1,1)_b,\ (1,1)_0$	

Multiplicity	Matter Additions				
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$		
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$
1	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	$(\overline{a},\overline{c}),\ (\overline{3},1)_{-\frac{2}{3}}$	$\Box\Box_c,\ (1,1)_1$
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$		
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$		
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$

Developments in F-Theory

Vafa'96..

F-theory – both geometric features of particle physics w/ intersecting branes & exceptional gauge symmetries common in the heterotic string & string coupling g_s -finite

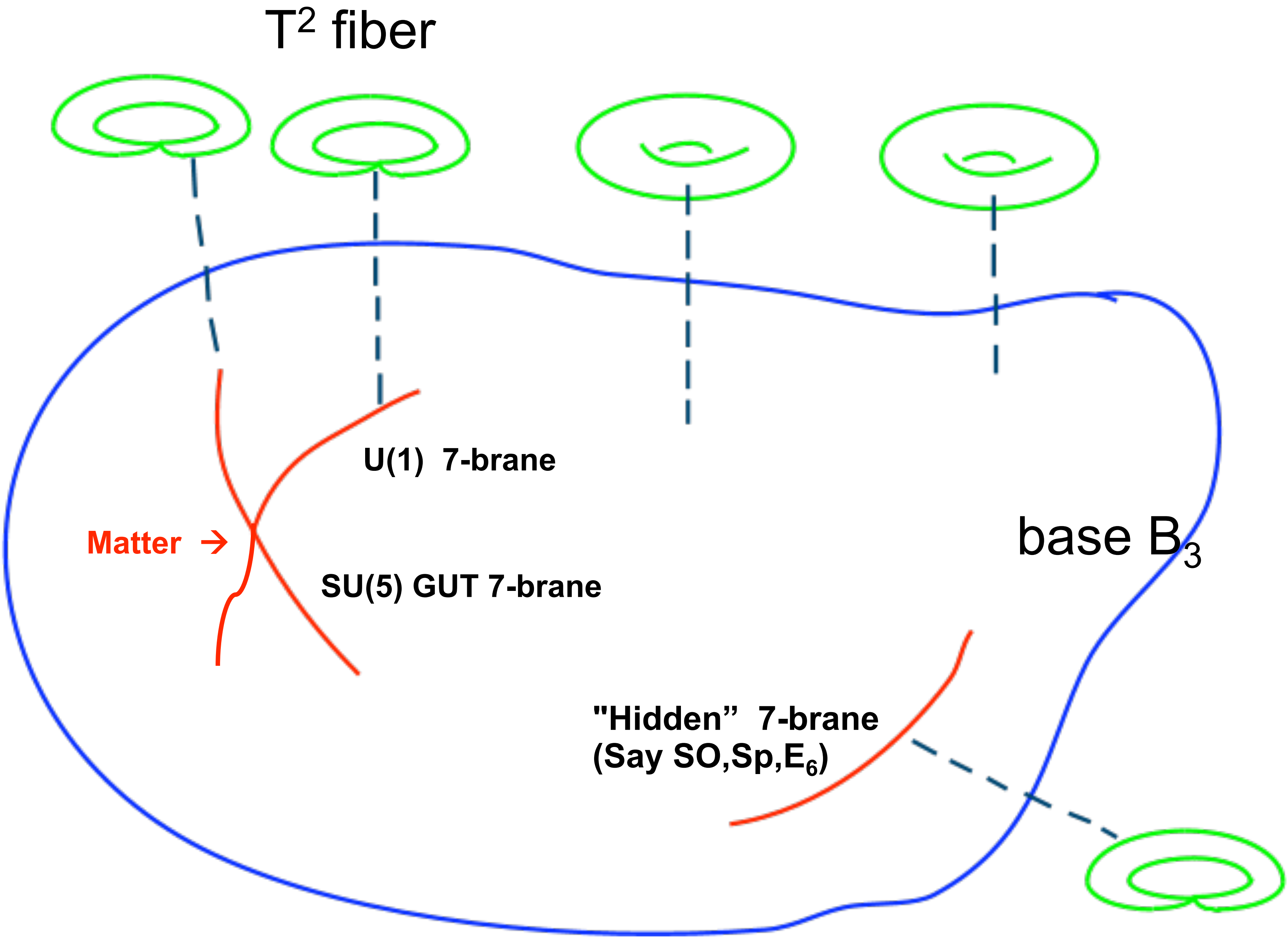
Geometry of F-theory: Elliptically Fibered Calabi-Yau four-fold (roughly viewed as a ``lift'' of Type IIB w/ 7-branes & g_s encoded in T^2 fibration over the base B_3) –Weirstrass parameterization

Where fiber degenerates (say for T^2 pA+qB cycle) a co-dim 1 singularity signified a location (p,q) 7-branes in the base B_3.

Matter: Intersecting 7-branes at co-dim 2 singularities G-flux needed (for chirality)

(Semi-) local &limited global SU(5) GUT studies: appearance of chiral matter (and Yukawa couplings) by studying co-dim two (and three) singularities on the GUT 7-brane. [Donagi, Wijnholt; Beasley, Heckman, Vafa; Marsano, Schafer-Nameki,Saulina; Blumehagen, Grimm, Jurke, Weigand;... M.C., Garcia-Etxebarria,Halverson 1003.5337...]

→ c.f. J. Marsano's; Luedeling's talk in the morning parallel session



T2 fiber
U(1) 7-brane
Matter
SU(5) GUT 7-brane
base B3
"Hidden" 7-brane
(Say SO,Sp,E6)

F-Theory and Instantons → Why Instantons?

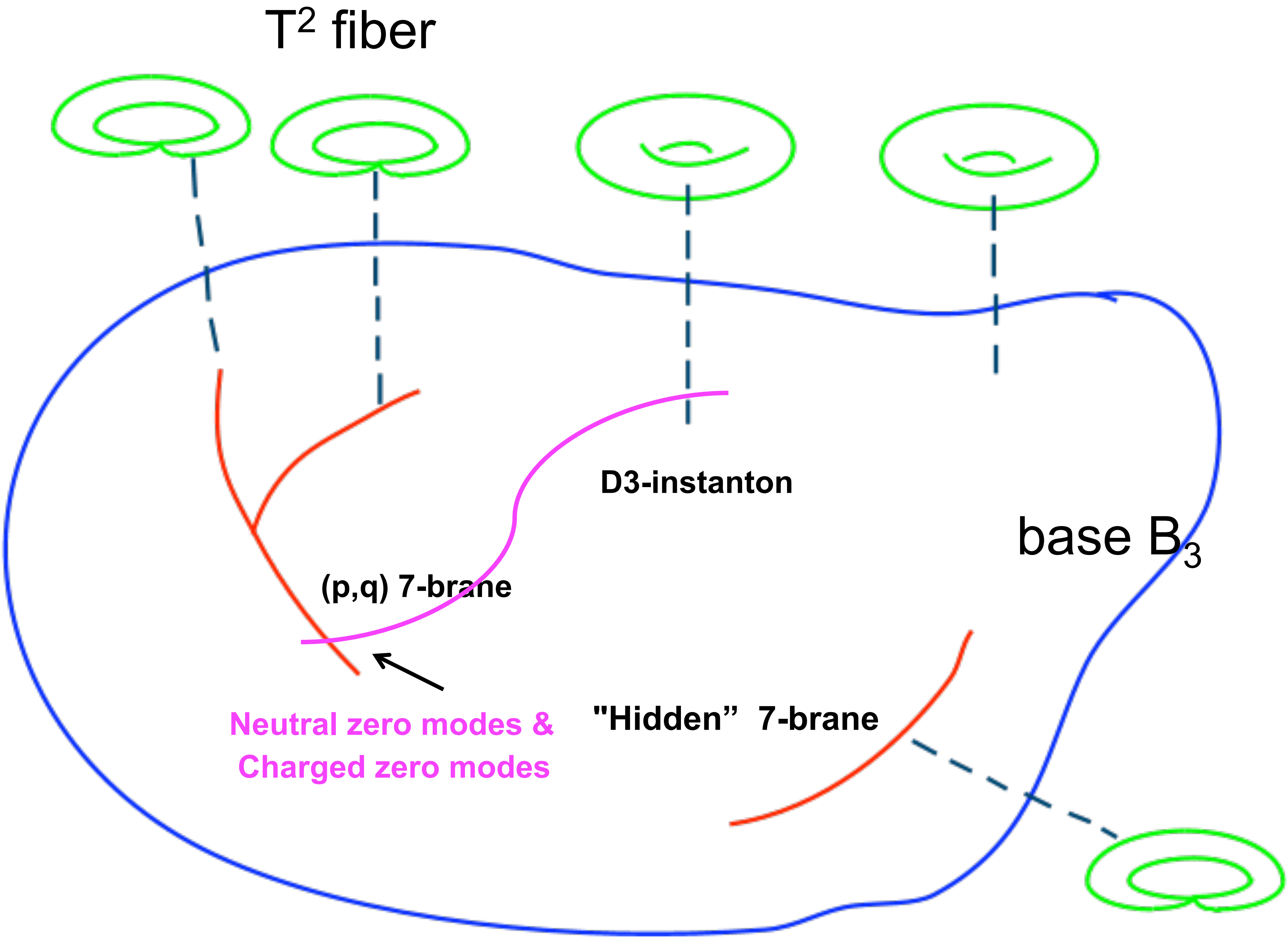
Still there (though may not be needed for 10 10 5):
other charged matter couplings w/hierarchcial couplings, moduli stabilization, supersymmetry breaking

[M.C., I. Garcia-Etxebarria, J. Halverson 1107.2388;
M.C., I. Garcia-Etxebarria, R. Richter 0911.0012]

Goal: i) identify zero modes
ii) quantitative superpotential
(including exceptional singularity points)
finite g_s → techniques ``indirect''

Three approaches: a) anomaly inflow - quantify neutral zero modes
b) string junctions - neutral & charged zero modes
c) F-/Heterotic duality - quantitative superpotential

Related Recent works (more focus on G-fluxes and U(1)'s):
[Marsano, Saulina, Schafer-Nameki 1107.1718;
Bianchi,Collinucci, Martucci 1107.3732;
Grimm,Kerstan, Palti,Weigand 1107.3842]



T2 fiber
D3-instanton
base B3
(p,q) 7-brane
Neutral zero modes &
Charged zero modes
"Hidden" 7-brane

Gauge Dynamics and Spectrum via String Junctions
7-branes in F-theory:

Complexified string coupling:

going around a D7-brane, $\tau \mapsto \tau + 1$. $\tau = C_0 + \frac{i}{g_s}$

there are more general 7-branes, for which $\tau \mapsto \frac{a\tau + b}{c\tau + d}$. where

$$M = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2, \mathbb{Z}).$$

if the cycle $pA + qB$ pinches off in the auxiliary torus, corresponding brane is a (p,q) 7-brane.

$$M = \begin{pmatrix} 1 + pq & -p^2 \\ q^2 & 1 - pq \end{pmatrix} \in SL(2, \mathbb{Z}).$$

Common building blocks:

$$A = (1, 0) \qquad B = (1, -1) \qquad C = (1, 1)$$

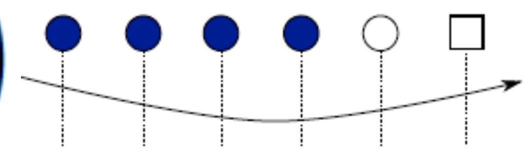
A-branes are D7-branes.

in F-theory, O7's split into B and C, seperation set by g_s.

$\rightsquigarrow$ so $\mathcal{M}_{O7} = M_C M_B$.

from IIb, know 4 D7's on top of O7 has SO(8), so

$$\rightsquigarrow \quad \mathcal{M}_{SO(8)} = M_C M_B M_A^4 = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$



can also get exceptional branes, e.g.

$$\mathcal{M}_{E6} = M_A M_C^2 M_B M_A^4 = M_A M_C \mathcal{M}_{SO(8)} = \begin{pmatrix} -1 & 1 \\ -1 & 0 \end{pmatrix}.$$

<u>Neutral modes</u> for F-theory O(1) instantons & SL(2,Z) mondromy

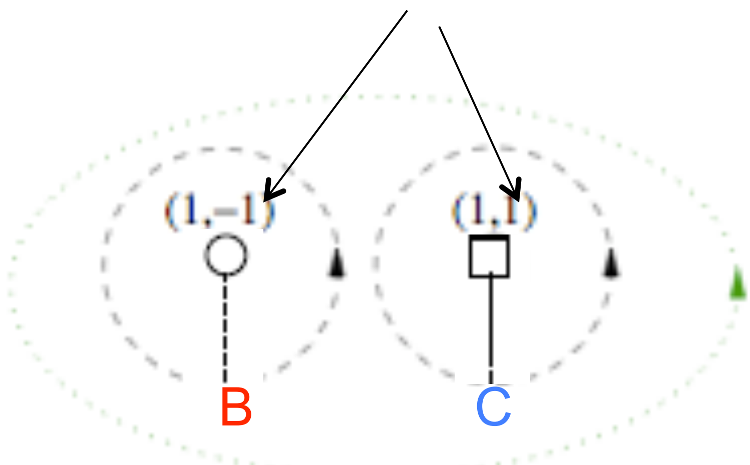
[M.C., I. Garcia-Etxebbaria, R. Richter, 0911.0012]

Absence of $\bar{\tau}$ in F-theory:

D3 O(1) instanton w/ O7- plane as complex co-dim 1 defects on the world-volume of D3 instanton:

O7 as two mutually non-local (p.q) 7-branes B & C [Sen'96]

w/ SL(2,Z) monodromy:



$$M_{(p,q)} = \begin{pmatrix} 1-pq & p^2 \\ -q^2 & 1+pq \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

Zero modes (``gauginos'' of E3) transform as [Kapustin,Witten'06]

$$\theta \rightarrow e^{i\varphi(M_{(p,q)})}\theta$$
$$\bar{\tau} \rightarrow e^{-i\varphi(M_{(p,q)})}\bar{\tau}$$

After the action around both defects

$$\theta \rightarrow \theta$$
$$\bar{\tau} \rightarrow -\bar{\tau}$$

Projected out!

[M.C., I. Garcia-Etxebarria, J. Halverson, 1107.2388]

Neutral modes for F-theory O(1) instantons

Further quantified results for θ modes via anomaly inflow:

Anomaly of the bulk CS action of intersecting D3-inst. and O7←→
Cancelled by zero modes at the intersection
(precisely fixed by θ modes , employing [Harvey, Royston'08])

Prototype: F-theory on elliptically fibered K3 --T^2 fibered over **P1**, w/Weirstrass:

$$y^2 = x^3 + fx + g \qquad \text{discriminant: } \Delta = 4f^3 + 27g^2$$

$$f \in H^0(\mathbb{P}^1, \mathcal{O}(4\overline{K}_{\mathbb{P}^1})) \text{ and } g \in H^0(\mathbb{P}^1, \mathcal{O}(6\overline{K}_{\mathbb{P}^1}))$$

w/ deformation ε:

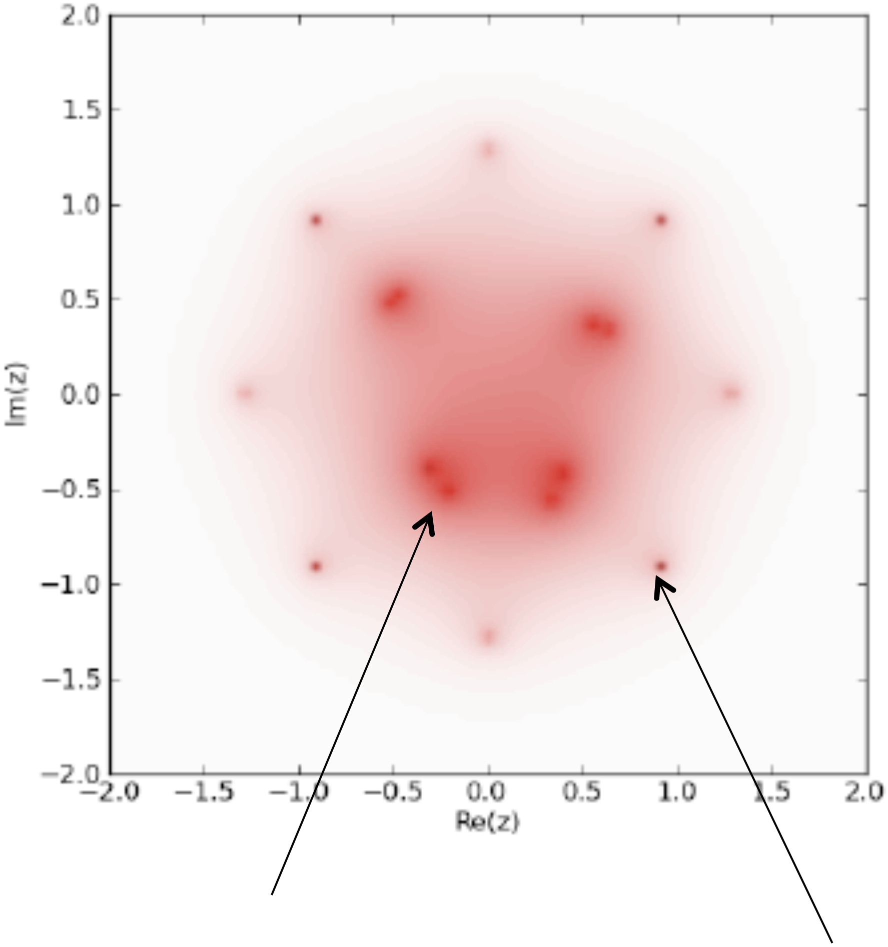
$$f = -3h(z)^2 + \epsilon\eta(z) \qquad h(z) = \prod^4 (z - h_n)$$

$$g = -2h(z)^3 + \epsilon h(z)\eta(z) \qquad \eta(z) = \prod_{n=1}^{8} (z - \eta_n)$$

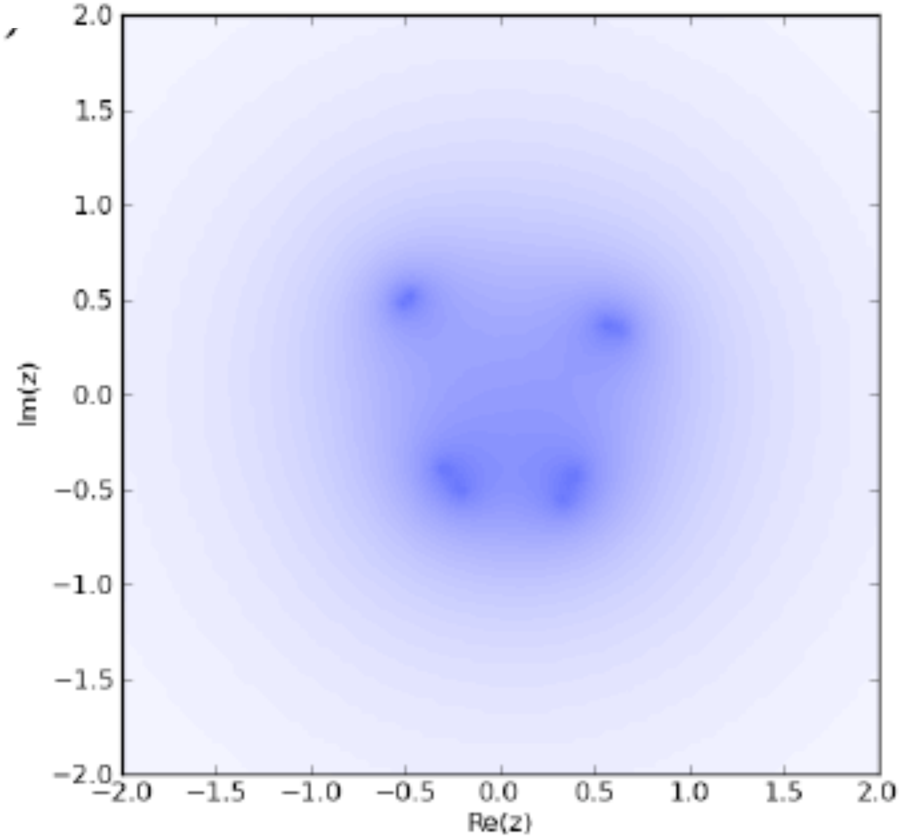
Geometrically: motion of 16 A [D7] & 4(B, C) [O7]–branes in **P1**

Numerical Results:

discriminant Δ



θ-mode wave function



(B,C) [O7]-branes   A [D7]-branes

Charged Zero Modes in E3-background:

D3 –instanton (complex dim 2) world-volume & w/ (p,q) 7- branes co-dim 1 defects moving as we move in moduli space.

Example w/(p,q) branes where the string coupling remains constant

Prototype: F-theory on elliptically fibered K3 w/ Weirstrass fibration:

$$y^2 = x^3 + fx + g \qquad j(\tau) = \frac{4(24f)^3}{4f^3+27g^2}$$

$$f \in H^0(\mathbb{P}^1, \mathcal{O}(4\overline{K}_{\mathbb{P}^1})) \text{ and } g \in H^0(\mathbb{P}^1, \mathcal{O}(6\overline{K}_{\mathbb{P}^1}))$$

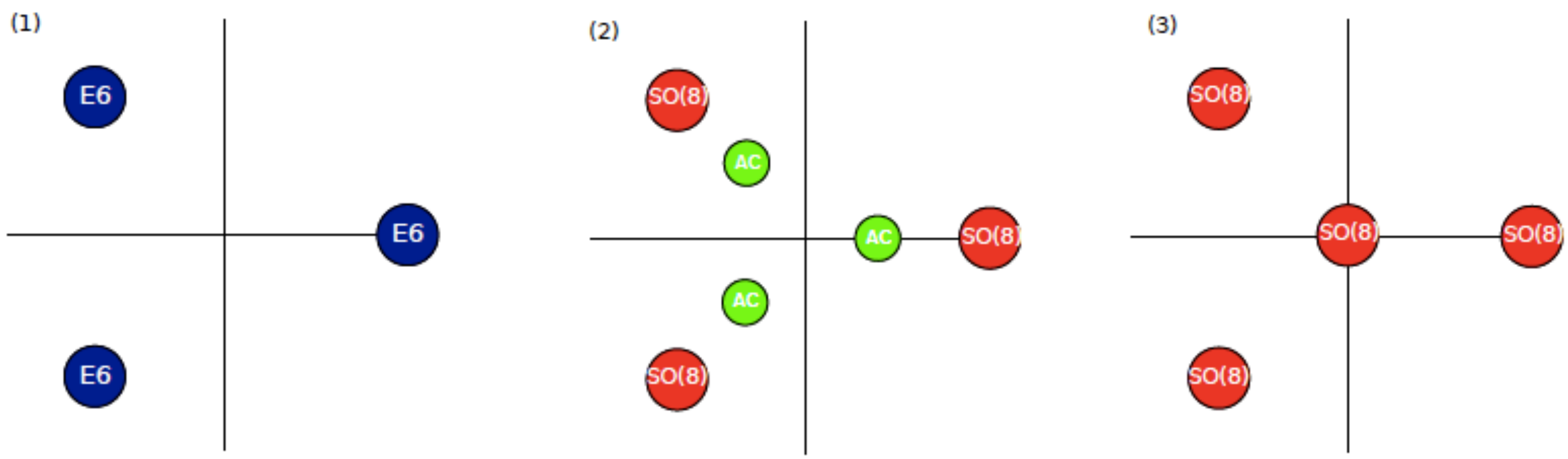
$$f(z) = \alpha(\phi(z))^2 \text{ and } g(z) = \phi(z)^3$$

with $\phi(z) = \prod_{i=1}^{4}(z - z_i)$ $\qquad j(\tau) = \frac{55296\alpha^3}{4\alpha^3+27}$ Constant $\tau = e^{\frac{\pi i}{3}}$!

Motion in (complex structure) moduli space

recall $E6 = A^5BC^2$ and $SO(8) = A^4BC$

$f = 0$ $\qquad$ $g = \prod_{n\in\{0,1,2\}}(z - e^{\frac{2\pi n i}{3}})^3(z - \beta\, e^{\frac{2\pi n i}{3}})$



$\beta = 1$ $\qquad$ β intermediate $\qquad$ $\beta = 0$

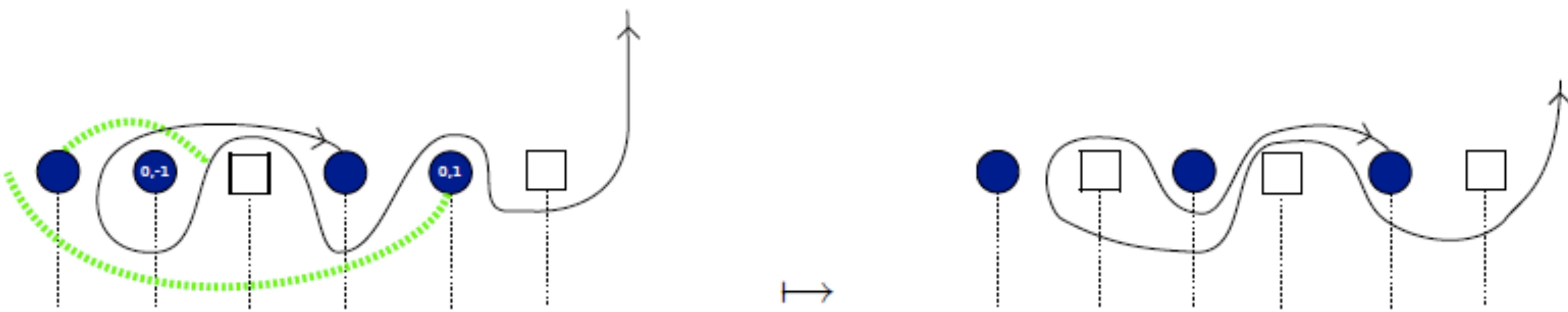
comments

- at $\beta = 0$, can go to weak coupling and then split to 16 D7 + 4 O7
- summary: smoothly go $E6^3$ → SO(8)^4 → 16 D7 + 4O7 at $g_s \ll 1$, constant coupling the whole way.

$ACACAC \leftrightarrow A^4BC$

complication: fourth $SO(8)$ appears as $ACACAC$, not A^4BC.

$\rightsquigarrow$ Need to "untangle" to understand junctions



In the D3-instanton backround (p,q) branes move and the spectrum of zero charged modes changes:

Starting with 3 **27**'s at $E6^3$ point.

Pulling AC off each E6, the strings in **27** which don't get a mass leave behind precisely an $\mathbf{8}_v$ of $SO(8)$.

Each AC has a string connected to the A-brane. Together with 5 massive states which become massless when the 3 AC's come together, they form an $\mathbf{8}_v$ of $SO(8)$.

Pushing to weak coupling and splitting $SO(8)$ to $16D7 + 4O7$, we get standard charged modes, i.e. D7-D3 strings.

Neutral and charged zero modes understood, including at exceptional symmetry points in moduli space!

How about quantitative superpotential?

Insights from Heterotic/F-theory duality

no time

move in vector bundle moduli space, can get jumps in zero modes which cause superpotential to vanish.

$\Updownarrow$

on F side, vanishing of instanton superpotential corresponds to brane movement / enhancement

Foresee further progress:

a) DEVELOPMENT of TECHNIQUES! → generalize constructions to general Calabi Yau spaces (advanced algebraic geometry techniques); Fluxes in F-theory

b) Quantitatively improve realistic model constructions, including further progress on non-perturbative effects

Conclusions/Outlook

``Glimpses'' of particle physics from String Theory
Focus on D-branes → Type II and F-theory

a) Progress: development of techniques for constructions
Sizable number of semi-realistic models

b) "The devil is in the details!"-typically not fully realistic
typically exotic matter → but viewed as a string prediction

MANY SOLUTIONS! Which one is our world?

$\Rightarrow$ input from Fermilab & Large Hadron Collider

Hopefully, with this input and theoretical developments
fully realistic particle physics from string theory
w/ efforts presented here playing a role